EFFECT OF KIND AND NUMBER OF MEASURED TREE HEIGHTS on lodgepole pine site-quality estimates

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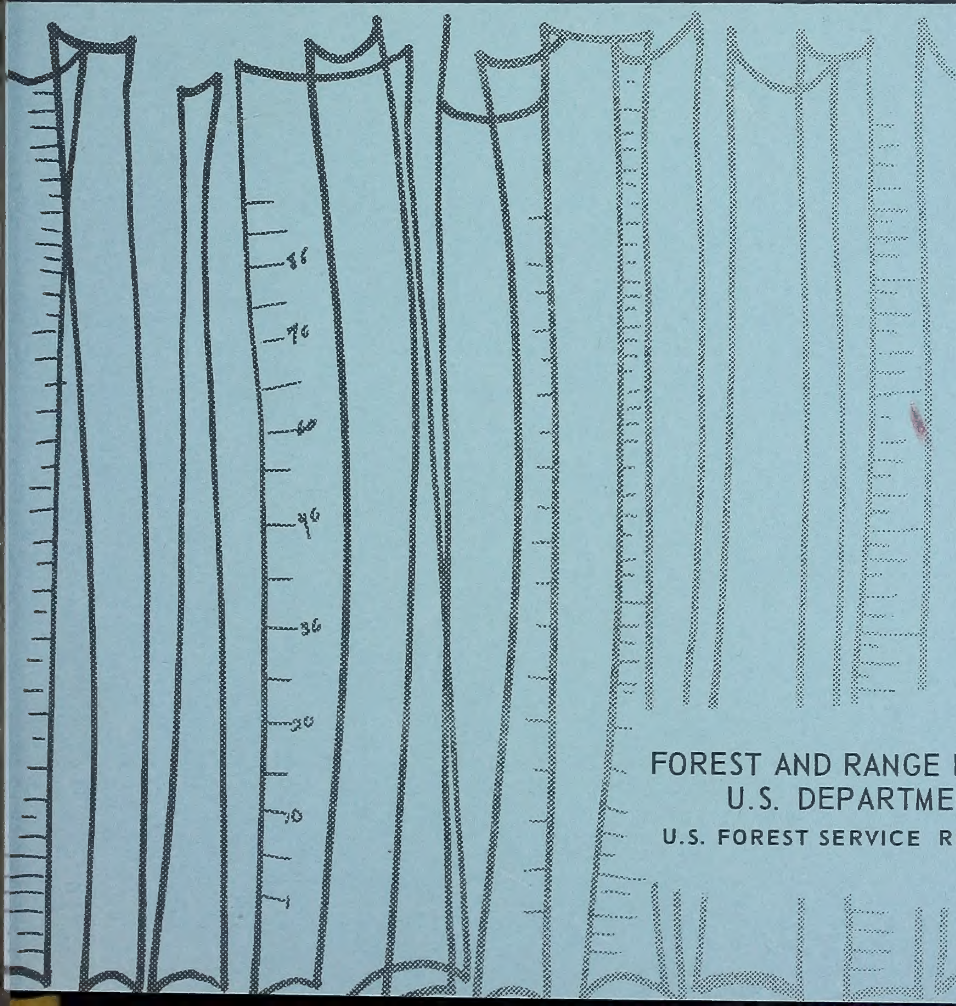

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INTRODUCTION

Site index based on tree height and age has become the most widely used method of estimating forest site quality. This paper discusses the relationship between kind and number of tree heights used and the reliability of the resulting site-quality estimates for lodgepole pine *(Pinus contorta)*. Effect of number of tree ages determined from ring counts is also discussed in a limited way.

Site class (site quality) is defined in "Forestry Terminology" (Society of American Foresters 1950)[1] as, "A designation of the relative productive capacity of a site with reference to the species employed; the volume or average height of dominant and codominant trees at a given age is usually used as standard for classification." Note that productive capacity is the real measure of site quality; average height of dominant and codominant trees is only the means of classifying. If another kind of height is found to be better correlated with productive capacity than average height of dominant and codominant trees, it stands to reason that this other kind of height would be a better means of classifying site quality. The study reported on in this paper compared effectiveness of various kinds of height for classifying site quality by comparing correlation between these kinds of height and measured production on a series of plots.

[1] Names and dates in parentheses refer to Literature Cited, p. 8.

Productive capacity implies total production from a fully stocked stand including mortality and thinnings for an entire rotation. Such figures are almost impossible to obtain. However, current gross annual cubic-foot increment is almost as good. Indeed, Bates (1918) once stated, "The only final criterion of site quality is the current annual cubic-foot increment of a fully stocked stand of the species under consideration." Gross periodic annual cubic-foot volume increment was adopted as the measure of productive capacity or site quality for purposes of this study.

KINDS OF TREE HEIGHTS PRESENTLY USED

Site index in the United States is most commonly estimated from average height and age of dominant and codominant trees. However, as Spurr (1952) pointed out, other groups of trees have been used both here and abroad. For example, in Great Britain, top height, or average height of the 100 largest (diameter) trees per acre, is commonly used. On the European continent, average height of the 40 largest (diameter) trees per acre is the usual standard, except in Holland where tallest trees are used (Braathe 1957). In both the United States and Canada, some people have advocated average height of dominant trees (Staebler 1948, Ker 1952). Recently, Johnson (1965) has advocated use of largest (diameter) tree heights as a shortcut method for estimating site index for longleaf pine *(Pinus palustris)*. In Australia, Gray (1945) made a strong case for use of tallest trees for estimating site index in exotic plantations.

KINDS OF HEIGHT AND AGE COMPARED

Kinds of height here compared for possible use in classifying site quality include nearly all of the kinds reported in the literature. Following are the combinations of kind and number of tree heights actually compared:

1. Average height of tallest trees selected at the rate of 1, 2, and 3 trees per plot and 30 per acre.[2/]
2. Average height of largest (diameter) trees selected at the rate of 1, 2, and 3 trees per plot and 30 per acre.
3. Average height of dominant trees as estimated from 1, 2, 3 and 3 to 14 trees per plot.
4. Average height of dominant and codominant trees as estimated from 7 to 19 trees per plot.

Site index based on height and age of the single tallest tree per plot was also compared with site index based on the same height but average age of from 7 to 19 dominant and codominant trees per plot.

The two kinds of age compared for determining site index were age of the single tallest tree per plot and average age of from 7 to 19 dominant and codominant trees per plot.

METHODS

Data collected for a lodgepole pine yield study in 1957 and 1958 (Dahms 1964) provided the basis for the present analysis. There were 94 plots in all. Sixty-seven of them, all located in stands over 50 years of age, were one-fifth acre in size. The remaining 27 plots were located in stands 50 years of age or younger and were one-tenth acre in size.

Plots were widely scattered over the pumice soils of central and south-central Oregon. Data available from each plot included the following: stand age, gross cubic-volume increment, stand density, and heights of various kinds of trees. Several volume-increment-predicting equations and a set of site index curves were also available from the yield study.

The method used to compare site-quality estimating capacity of the various kinds of height was to compare their capacity to predict gross periodic annual cubic-volume increment. Volume increment was predicted from the three basic stand variables, age, height, and stand density, plus powers and cross products of these basic variables. The equation form[3/] chosen was $V.I. = a - b_1A - b_2CCF + b_3(H \times A^2) + b_4(H \times CCF) - b_5H^2 - b_6(H \times A \times CCF)$ where: a = constant, b_1 --- b_6 = coefficients to be calculated, A = age, H = height, CCF = crown competition factor,[4/] and $V.I.$ = gross periodic annual increment.

[2/] Thirty trees per acre means three trees per plot on the twenty-seven 1/10-acre plots and six trees per plot on the sixty-seven 1/5-acre plots.

[3/] The particular combination of variables was selected from age, CCF, height, height × age, height × age^2, height × CCF, height^2, and height × age × CCF after examining all 255 possible equations based on these eight independent variables with one form of height. The chosen form, the best four variable, and the eight variable equations were all calculated for each form of height to see if ranking of kinds of height was affected by equation form. Only very minor shifts in ranking took place from one equation form to another.

[4/] Crown competition factor (CCF) is a new measure of stand density developed by Krajicek, Brinkman, and Gingrich (1961). In essence it compares growing space available to a tree with the area of shadow the crown of an open-grown tree of the same breast-high diameter would cast on level ground with the sun directly overhead. CCF is used as the stand density measure because it is not strongly correlated with either site quality or age, as is basal area. Consequently, height is the only stand variable strongly correlated with site quality, a necessity when the goal is to compare various kinds of height as measures of site quality.

The comparison was made by calculating separate equations of this form for each kind of height. That equation which accounted for the most variation contained the most effective kind of height.

To see if relationships were consistent from one group of plots to another, the 94 plots were split into two groups of 47 plots each. Separate regressions were calculated for each kind of height within each group. Thus, it was possible to see if each kind of height held the same relative position within each group of plots.

A check on the volume increment comparisons was provided by a volume test. Precision of volume estimates obtained from various kinds of height was compared in stand volume formulas of the form $V = b(BH)$ where: V = cubic volume, BH = basal area × height, and b = the ratio $\frac{V}{BH}$. Separate ratios were calculated for each plot for each kind of height. That form of height that produced the average ratio with the lowest coefficient of variation[5/] was the most effective.

Methods used to compare kinds of age as a basis for entering the height-over-age curves of a site index system were similar to those used to compare kinds of height. Two site indices were calculated for each plot. One was based on height and age of the single tallest tree per plot. The other site index was based on the same height but average age of from 7 to 19 dominant and codominant trees per plot. Efficiency of these two kinds of site index were compared in a volume increment equation based on the stand variables, age,[6/] site index, and stand density (CCF) plus powers and cross products of these basic variables. The equation was calculated with first one kind of site index and then the other. That equation which accounted for the most variation contained the best site index.

[5/] Coefficient of variation is the standard deviation of individual plot ratios expressed as a percent of the average ratio.

[6/] Stand age in the volume increment predicting equation was average age of from 7 to 19 dominant and codominant trees per plot, regardless of which kind of site index was used.

RESULTS

Volume-Increment Correlations

Height of tallest trees was, on the average, the most effective form of height for estimating volume increment (site quality). Heights of dominant and of largest (diameter) trees followed in that order (table 1). Heights of tallest trees were consistently better than heights of largest (diameter) trees whenever equal numbers of trees were compared. The position of dominant tree heights between that of tallest and largest (diameter) was somewhat erratic. Average height of three dominant trees was more effective than average height of three trees of any other kind. However, average height of two dominants was less effective than average height of two trees of any other kind (table 1).

Effectiveness of average height of dominant and codominant trees was not as directly comparable as other kinds of height because a specific number of trees was involved. However, it is clear that codominants were less effective than dominants. Average height of all measured dominants and codominants (average 13 per plot) was less effective than average height of the dominants only (average 9 per plot). Average height of three dominants was also slightly more effective than that of all dominants and codominants. Thus, addition of an average of four codominant heights per plot actually reduced effectiveness below that obtained from either nine or three dominants alone.

Table 1.--Precision of gross cubic-foot volume increment estimates for 13 kinds of height and consistency of relationships from one sample to another

Kind of height	Percent of variation accounted for by equation for--		
	All plots	Sample 1[1]	Sample 2
Average height of:			
30 tallest trees per acre[2]	76.5	78.1	77.1
3 tallest trees per plot	75.0	78.6	74.8
2 tallest trees per plot	74.3	77.6	74.2
Single tallest tree per plot	72.8	76.4	72.9
30 largest trees per acre	74.4	76.2	75.5
3 largest trees per plot	74.1	76.4	74.5
2 largest trees per plot	72.7	75.5	73.0
Single largest tree per plot	70.4	72.3	72.3
13 dominant and codominant trees[3]	75.7	77.1	76.1
9 dominant trees[4]	76.8	79.4	76.3
3 dominant trees	75.9	78.0	76.4
2 dominant trees	72.2	73.9	72.2
1 dominant tree	72.4	74.4	73.8

1/ Sample 1 consisted of all odd-numbered plots; sample 2, the even-numbered ones.

2/ Equivalent of the three tallest trees on a 1/10-acre plot or the six tallest on a 1/5-acre plot.

3/ Number of dominant and codominant tree heights measured on a plot ranged from 7 to 19 and averaged 13.

4/ Number of dominant tree heights measured on a plot ranged from 3 to 14 and averaged 9.

Increasing number of trees within a particular kind tended to increase precision of the volume increment estimate. The trend was consistent within tallest and largest (diameter) trees but not completely so in the case of dominant trees (table 1).

Relative rating of the various kinds and numbers of tree heights used was also consistent, with but minor exceptions, between the two samples (table 1).

Volume and Volume-Increment Correlations Compared

Kinds of height and number of trees rated in very similar order as predictors of either volume or volume increment. However, there were some exceptions.

Largest difference as predictors was in relative position of average height of dominant and codominant trees. This kind of height provided the best volume estimate of all. Possibly the better showing of dominant and codominant height over dominant height only was all due to increased number of trees. However, addition of codominant heights may have added something beyond mere numbers. This is in sharp contrast to the volume increment situation. There, addition of codominant heights to dominant heights actually reduced effectiveness for volume increment prediction purposes despite a greater number of trees.

Position of dominant heights relative to tallest and largest (diameter) heights was not entirely the same for predicting volume increment as for predicting volume. Dominant height was neither clearly better than largest (diameter) heights nor clearly poorer than tallest tree heights for volume increment predicting purposes. However, for volume predicting purposes, tallest tree height was definitely best, with dominant height clearly second best, and largest (diameter) height poorest.

Effect of Kind of Age on Site Index Reliability

Number of trees used to estimate age for purposes of site index determination made very little difference. Where site index was based on height of the single tallest tree per plot and average age of from 7 to 19 dominant and codominant trees, the volume increment equation accounted for 75.3 percent of all variation. The equation containing site index based on height and age of only the single tallest tree per plot accounted for 74.6 percent of total variation.

DISCUSSION

There appear to be valid reasons for the way various kinds of height are rated as estimators of volume increment or volume. Likewise, differences in rating between the two criteria seem to be based on definite reasons.

Failure of height and diameter to be perfectly correlated accounts for the poor showing of height of largest (diameter) trees. On some plots, tallest and largest trees were almost the same individuals, but on others they were not. In one rather extreme instance, all three of the largest (diameter) trees were codominants.

There appears to be a real reason for the different rating of average height of dominant and codominant trees by the volume and volume increment tests. As an example, one might visualize average height of all trees on a plot as being an excellent height expression for volume prediction purposes. However, this kind of height would be greatly affected by stand density because the number of

small partially suppressed tree heights included would vary with stand density. Consequently, an average height of all trees is not as expressive of site quality as an average height of only those trees that have largely escaped the depressing effects of suppression.

This effect of suppression also applies to dominant and codominant trees. Varying numbers of partially suppressed codominant trees were used to make up the average. These codominants were expressive of the particular volume-height relationship to be found on the individual plots. However, codominant heights were more affected by variations in density and in inherent ability to grow in height. Therefore, they were not as expressive of site quality and volume increment. Thus, the different ranking of average height of dominant and codominant trees by the volume and volume increment criteria appears to be reasonable.

The slightly different rating of dominant height by the volume increment and the volume criteria also seems reasonable. There is a stronger correlation between height and volume than between height and volume increment. Therefore, differences between dominant height and tallest tree height, and between dominant height and largest (diameter) tree height, stand out clearly against the smaller unexplained variation in volume. The larger unexplained variation in volume increment does not allow these differences to stand out so sharply.

Should a forester, faced with the task of estimating productivity of a given tract of land, measure many tree heights at each of a relatively smaller number of sampling locations on his tract or should he measure only one tree height at each of a few more locations? Results already examined showed that increasing number of tree heights measured at a given location increased precision of the site quality estimate. However, increasing number of locations was even more effective. For example, standard deviation[7/] of a productivity rating based on height of the single tallest tree at one location is ± 16.4 cubic feet. Increasing number of measured heights at one location to five reduced standard deviation to ± 15.4 cubic feet. For every 10 plots with five measured tree heights each, 11.3 plots with but a single measured height would be required.

The apparent advantage for measuring only one tree height per plot was artificially increased by failure to measure volume increment perfectly on the individual yield plots used to develop the volume increment equation. The situation is analogous to comparing the height difference between a 4-foot and a 5-foot tree with that between a 6-foot and a 7-foot tree. The absolute difference is the same in both cases, but the relative difference is much greater in the case of the smaller trees. Measurement errors increased size of mean square deviation from regression whether one tree or five were used. Therefore, the difference in volume-increment-predicting accuracy between height of a single tree and average height of five trees is relatively smaller compared with unexplained variance.

To better understand the effect of volume-increment measurement error, let us pretend we know its size and

[7/] Standard deviation, as used here, is the square root of the mean square of deviations from the particular volume increment predicting equation being discussed. Gross cubic-volume — increment values and, therefore, standard deviations also, are in terms of cubic feet per acre per year.

look at a hypothetical example.[8/] Let us assume that elimination of the measurement error reduced standard deviation of a productivity estimate for one tree height from ±16.4 cubic feet to ±11.6 cubic feet and for an average of five tree heights (on one plot) from ±15.4 cubic feet to ±10.1 cubic feet. Then, standard deviation of two single tree estimates (each taken on a different plot) would be $\pm\frac{11.6}{\sqrt{2}}$, or ±8.2 cubic feet. With measurement error eliminated as in this hypothetical example, the true accuracy advantage for measuring five tree heights on a plot rather than one is shown. The ratio of variances $\frac{102.68}{134.48}$ shows that 10 plots with five tree heights per plot are approximately the equivalent of 13 plots with but one measured tree height if the assumptions of the example are true.

No precise estimate of the size of volume-increment measurement errors in the original data is available. However, one equation[9/] used to estimate volume increment from the stand variables--age, CCF, and basal area--accounted for 83.8 percent of all variation in volume increment among plots. This equation was substantially more effective than any based on height, age, and CCF. We must realize, too, that an important part of the 16.2 percent of variation left unaccounted for by this equation also arose from failure of the basic stand variables--age, CCF, and basal area--to be perfectly correlated with volume increment. Thus, a large portion of variation from the equation predicting volume increment from the group of stand variables, including height, definitely did not stem from volume-increment measurement errors.

APPLICATION

There are some instances where the best site-quality estimate obtainable for a given plot is desired. One such situation would be where an effort is being made to correlate soil characteristics with site quality. Under such circumstances, many tree height measurements may be called for on a rather limited plot area.

Productivity estimates for large tracts of forest land are probably a more common need. They are usually obtained by estimating site quality at a number of sampling points. The goal is to balance expenditure of effort spent at each point against that spent moving between points in such a way that a tract estimate of specified reliability will be obtained at lowest cost. Because gain from increasing number of trees measured at a given point is small, greatest efficiency is likely to result from measuring only one or possibly two tree heights at a point.

All of the ideas presented in this paper are built on the assumption that stand density where tree heights are to be measured is low enough so that height growth of at least the leading trees has not been reduced by excessive competition. Smithers (1956), Holmes and Tackle (1962), and others have shown that overdensity can sharply curtail height growth of lodgepole pine.

[8/] For this example, the mean square of deviations from the single tree regression was halved (half assumed due to measurement error) and its square root extracted as follows:

$$\sqrt{\frac{16.4^2}{2}} = \sqrt{134.48} = \pm 11.6$$

The quantity $16.4^2 - 15.4^2$ or 31.80 was then subtracted from 134.48 to give 102.68. The quantity, $\sqrt{102.68}$ or ±10.1, was used as the standard deviation of a site-quality estimate based on average height of five trees at a location. Although this example is purely hypothetical, the writer believes it is in the general area of the truth.

[9/] This equation was $V.I. = 84.4 - 2.268A + 0.01326A^2 + 1.431B - 0.00693(A \times B) - 0.512CCF + 0.001567(CCF \times B)$, where: $V.I.$ = gross per-acre annual cubic-volume increment, A = stand age, B = basal area, and CCF = crown competition factor. The above equation was derived from the same lodgepole pine yield data used for the present site quality analysis.

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